



Modeling Climate Impacts on Agricultural Output in South Korea: Evidence from Artificial Neural Networks

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Abstract. Agriculture in South Korea, even with its limited share in the national economy, remains critical for food security, rural livelihoods and regional resilience. This study investigates the impact of climate change on agricultural gross domestic product in South Korea using advanced machine learning techniques. The model chosen in this research was trained using historical climate and economic data from 1990 to 2020 and validated using cross regional application to 26 Asian countries. Results indicate that precipitation is the most influential climatic variable across the four variables chosen, especially in water-intensive, rice producing provinces. While temperature plays a big role in colder, high-altitude regions. Wind speed on the other hand, exhibits minimal influence except in specific microclimates. Also, in this study, forecasted agricultural GDP projections for the year of 2030 were generated, underlining regional disparities in future climate vulnerability. Furthermore, this study proposes targeted and tailored climate-smart policy recommendations on a provincial level. Overall, this research demonstrates the value of machine learning in climate agriculture modeling and offers a scalable framework to inform adaptive policy recommendation in South Korea's evolving agriculture and climate landscape.

Keywords: Climate change · South Korea · Machine learning · Agricultural GDP · Artificial Neural Networks · Adaptation strategies

1 Abbreviations:

T2M	Temperature at 2 meters
RH2M	Relative Humidity at 2 meters
PRECTOTCORR	Corrected Total Precipitation
PRECTOTCORR_SU	Sum of Corrected Total Precipitation
M	
WS2M	Wind Speed at 2 meters
T2M_MAX	Maximum 2-meter Temperature
T2M_MIN	Minimum 2-meter Temperature
QV2M	Specific Humidity at 2 meters
AGRI_GDP	Agricultural Gross Domestic Product
GDP	Gross Domestic Product
ANN	Artificial Neural Network
R²	Coefficient of Determination
RMSE	Root Mean Square Error
MAE	Mean Absolute Error
NASA	National Aeronautics and Space Administration
KMA	Korea Meteorological Administration
IPCC	Intergovernmental Panel on Climate Change
FAO	Food and Agriculture Organization
FACE	Free-Air CO ₂ Enrichment
IPDM	Integrated Pest and Disease Management

2 Introduction

In the 21st century, climate change has posed one of the most formidable challenges both to global food systems and rural economies worldwide. With multifaceted impacts, spanning from shifting rainfall patterns and rising temperatures to increasing frequency of extreme weather events, encompasses a broad spectrum of environmental shifts. Posing direct threats to agriculture and food security all around the globe [6, 8]. It is undeniable that these effects make the countries with economies mostly dependent on agriculture the most vulnerable, it is also undeniable that the technologically advanced nations with diversified economies also suffer for climate change impacts. For example, South Korea is also not immune to climate variability, as it is known with its diverse agricultural systems and sharp seasonal contrasts as well as a mountainous landscape making it sensitive to climate perturbations.

In the global climate-agriculture context, the East Asian country of South Korea presents a paradox. Although its agriculture sector accounts for less than 2% of its national GDP as of 2023, the sector plays a strategically important role in terms of food sovereignty, rural employment and cultural heritage. Even with the country's transition from subsistence to high-tech agriculture, it has not eliminated its exposure to climate variables impacting its agricultural productivity. In fact, increased intensification, mono-cropping and reliance on water-intensive crops such as rice, increases its vulnerability to climate stress. Highlighting the challenge in measuring the climate impact on the country's agriculture and the importance of forecasting how these impacts are likely to evolve, allowing the nation to implement tailored province-specific adaptation strategies.

Historically, studies on the climate impacts on agricultural productivity in South Korea often relied on conventional econometric methods, such as linear regression and panel data models. These approaches may struggle to fully capture the nonlinear and multidimensional interactions between the climatic variables and agriculture. Machine learning in this subject offer a more powerful alternative, specifically Artificial Neural Networks (ANN), allowing for a more effective modeling of complex systems where traditional statistical assumptions fail.

This study addresses a central question: How do climatic variables influence agricultural GDP across South Korean provinces, and which factors drive regional vulnerability under future climate conditions?

To answer this, the paper utilizes ANN models trained on historical climatic and economic data. This allows us to not only examine the past and present correlations between agriculture productivity and climatic variables but also provides forecasted provincial-level GDP estimates for 2030 under evolving climate conditions. The study further evaluates the climatic variables importance in identifying which climate drivers impacts which province the most, providing insightful and pivotal data allowing for a targeted design for climate smart agricultural policies.

By combining machine learning techniques [7, 9] with climate and economic datasets, this research aims to provide a tailored, actionable framework for understanding and addressing climate vulnerability in South Korea's agriculture sector across all of

its province. Thus, contributing to both the academic literature and real-world policymaking in the era of climate uncertainty in the region.

3 Literature review

3.1 Global agricultural vulnerability to climate change

Agriculture has always been recognized globally as one of the sectors most susceptible to the negative impacts of climate change. No continent has been immune to climate change and everything accompanied with it, such as increased average temperatures, extreme weather events, floods, droughts, typhoons, wildfires, heatwaves, changes to the precipitation patterns and the list goes on. The variability in climatic patterns has significantly influenced agricultural systems all around the globe, global agricultural systems are universally affected from these detrimental effects. South Korea was no exception, even in the scope of its highly characterized degree of modernization in agricultural production, it faces structural and climatic challenges that shape its long-term economic outlook. This research aims to evaluate how climate change impacts South Korea's agricultural GDP using machine learning. In the hopes to understand the impacts of climate change on the economy of a highly modernized and advanced country like South Korea.

3.2 Empirical evidence of climate impacts on crop yields and economy

Over the past decades, climate change has impacted agricultural systems worldwide, emerging as a primary driver of one of the major contributors to the decline in global agriculture performance. Global-scale studies, such as those by Lobell et al.[11] and Zhao et al.[16], underline an ongoing decreasing trend in crop yields, more precisely maize, soybeans and wheat. This is mainly due to increased temperatures and irregular precipitation patterns, prolonged droughts and more frequent extreme weather events. [11,16]. Zhao et al. emphasize that global yields decreased between 3.1% and 7.4% for every 1°C rise in global mean temperature. In addition to this, climate variability has a significant impact on the economy. According to Burke et al.[3] and Diffenbaugh& Burke[4], there is a nonlinear relationship between temperature and economic output, emphasizing economic ramifications of climate anomalies and indicating that nations operating outside the optimal range for economic productivity, being 13°C, face severe productivity losses and tend to suffer substantial losses. These insights are pertinent for South Korea, a temperate country which lies in a climatic transition zone and faces a blend of subtropical and temperate climate conditions.

3.3 Case Study: Morocco's Regional Climate-Agriculture Dynamics

While global trends establish the broad vulnerability of agriculture to thermal and pluvial shifts, regional studies provide the necessary granularity to understand how

these forces manifest in specific administrative zones. A pertinent example is the recent analysis of Morocco's regional climate-agriculture dynamics. This study is methodologically significant for the South Korean context as it also utilizes NASA MERRA-2 and World Bank datasets to model diverse topographical regions using machine learning from 1990 to 2022. This study done by En-Nia et al. (2025)[5] employed machine learning models, precisely: Random forest, Lasso regression and Artificial neural networks, explored the relationship between climatic variables and agricultural GDP across all Morocco 12 regions. This study identified temperature as the most critical factor consistently having a negative impact on agriculture, heat stress especially in arid areas in the south like in the region of DrâaTafilalet. On the other hand, precipitation and wind speed showed regionally variable and more heterogeneous effects. In some areas rain and wind enhanced productivity through pollination and rainfall while in some other areas it caused erosion and flooding contributing to yield loss. However, relative humidity demonstrated limited predictive power. Finally, among the three models tested, random forest proved to be having the best predictive accuracy, with an R^2 of 0.699 (see equation 4), highlighting its robustness in capturing nonlinear climatic interactions with agriculture output. This highlights the importance of testing different models to tailor adaptation strategies to regional climatic contexts and finding region specific adaptation policies that strengthens the climate resilience in the Moroccan agricultural sector across all its regions.

3.4 South Korea's Climatic and Agricultural Context

Regionally, East Asia and the Korean peninsula especially stand out for their sharp seasonal changes and their growing vulnerabilities to extreme weather events, more notably during summer monsoon and typhoon seasons. According to the Korea Meteorological Administration (KMA, 2022), the country has known increased average temperature over the past century, rising annually by around 1.8°C , a number higher than the global average. Furthermore, rainfall variability has become more erratic with intense downpours occurring more frequently and over shorter periods. Although agriculture accounts for a relatively modest share of South Korea's GDP, being around 2% of the country's GDP as of 2021, it plays an outsized role in South Korea's social fabric and long-term resilience. Even with its small GDP share, agriculture in the East Asian country supports a large rural population and plays a significant role to the country's food security and cultural heritage. Agricultural land occupies roughly 16% of Korea's land area, and a large proportion of this is concentrated in fertile plains such as those in Jeollabuk-do and Gyeonggi-do. The regional diversity in agriculture, from citrus farming in Jeju to rice and ginseng in central provinces, means that the impacts of climate change are unequally distributed across the country.

3.5 Limitations of Traditional Econometric Approaches

Past studies on the impact of climate change on agriculture in South Korea has always been examined through standard econometric models. For example, studies done by Kim et al.[10] and Park & Seo[12] used panel regression and crop specific yield data

to estimate the impact of temperature and precipitation changes on crop productivity. While such studies, are indeed insightful in their own way, they often rely on rigid and strict linear assumptions and tend to oversimplify the multifaceted, non-linear nature of climate-agriculture dynamics. These models also tend to struggle to capture the intricate local microclimatic variations or the complex interaction between the many variables and factors that are increasingly relevant in Korea's diverse terrain. In this scope machine learning presents a valuable paradigm for accurately modeling the complex and nonlinear relationships between climate change and agriculture, especially in South Korea. While studying complex relationships like the one in hand, traditional econometrics models may fall short in accounting for the multidimensional and interdependent nature of the relationship between the climatic factors and agriculture. Advanced machine learning models, such as random forests, artificial neural networks, and lasso regression, offer improved predictive power and deeper insights into variable importance. In this scope Studies by Xu & Liu[14] and Zhang & Liu[15] demonstrated the effectiveness of ANN in forecasting crop yields based on seasonal climatic predictors in East Asia. Similarly, (Zhang and Liu 2022[15]) illustrated the utility of machine learning techniques in optimizing crop management decisions and enhancing crop management practices and the resilience of agriculture to climate variability.

3.6 Research Gap and Justification for This Study

In the South Korean context, while numerous studies have explored the impact of climate change on agriculture, few have harnessed machine learning at a national scale to predict broader economic indicators such as agricultural GDP using climate inputs, highlighting the novelty and relevance of this research. Existing studies often focus on crop-specific yield forecasts or regional analyses that overlook broader economic indicators. Moreover, many of these studies rely on linear models that often fail to capture the complex, nonlinear interactions between climatic variables and economic outcomes. By integrating high-resolution climate data, such as temperature, precipitation, wind speed, and humidity with national agricultural GDP figures, this research leverages machine learning algorithms, precisely Artificial Neural Networks to uncover hidden patterns and regional disparities[1] in climate sensitivity. This methodological approach not only improves predictive accuracy but also provides actionable insights for adaptive policy-making, thus marking a significant advancement in understanding climate-agriculture dynamics in South Korea. The application of machine learning to model agricultural GDP at this scale remains under explored in the Korean context, reinforcing both the originality and policy relevance of this study. This study contributes to the literature by modeling agricultural GDP sensitivity to climate variables at the provincial level using machine learning.

4 Materials and Methods

4.1 Study area

South Korea, officially called the Republic of Korea, is an East Asian country, located to the southern half of the Korean Peninsula, bordering North Korea to the north, with the Yellow Sea to the west and the Sea of Japan to the east. Its surface accounts for 100210 square kilometers. Its geography is largely mountainous, accounting for around 70% of its land area, with fertile plains concentrated in the west and south, making those regions vital for agriculture, while over 3000 islands, including Jeju island add to its geographic diversity. When it comes to its climate, South Korea experiences a temperate climate with four distinct seasons. During the winter months from December to February, the weather is cold and dry, with average temperatures going from 0°C to -10°C in the north. In the south, temperatures are about 5-10 degrees higher. With snow occasionally falling during this time period. In spring March to May, it is mild and pleasant, with temperatures between 10°C and 20°C. While summer going from June to August, is hot and humid with temperatures between 25°C and 35°C. Finally, Autumn goes from September to November is rather mild and dry, with temperatures range around 10 and 20°C.

South Korea is administratively divided into 17 first level regions, including a mix of provinces, metropolitan cities, a special city and a special self-governing province. Its agroclimatic scope shaped by its temperate, monsoon influenced climate and mountainous topography, characterizing its varied agricultural potential across regions. However, South Korea's agriculture contributes a relatively small share to its GDP. Accounting for 1.6% as of 2023, highlighting the country's transition into a more advanced, industrialized economy.

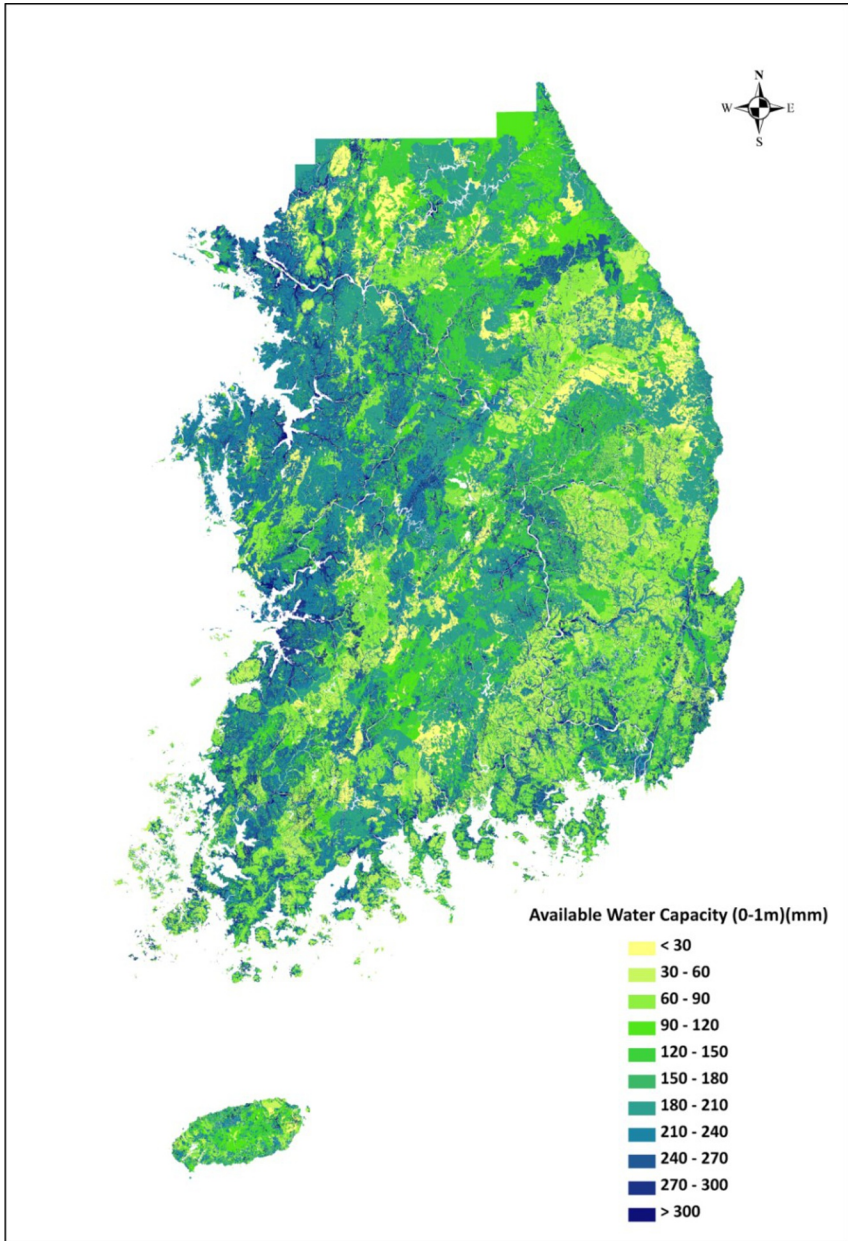


Fig. 1.water availability in South Korea

Source: Predicting and mapping soil available water capacity in Korea.

4.2 Data sources

In this study we used data mainly from NASA's POWER Data Access Viewer, available at <https://power.larc.nasa.gov/>, while agricultural GDP data was retrieved from the World Bank Open Data portal at <https://data.worldbank.org>. To ensure comparability over time, the agricultural GDP data, initially reported in current U.S. dollars, were converted to constant prices using the World Bank's GDP deflator thus accounting for inflation. This adjustment was crucial to ensure that the analysis captures real growth in agricultural output rather than nominal price changes. Data pre-processing played a crucial step to prepare it for machine learning applications. This step involved systematically collecting, aggregating, cleaning, and transforming the raw datasets. Climate data covering the period from the years 1990 to 2020 for Asian countries were sourced from NASA's MERRA-2 reanalysis database. Which provides a set of key climatic variables that were then selected to represent the primary meteorological factors influencing agricultural productivity. These included land surface temperature (TS), 2-meter air temperature (T2M), maximum and minimum 2-meter temperatures (T2M_MAX, T2M_MIN), specific and relative humidity at 2 meters (QV2M, RH2M), wind speed at 2 meters (WS2M), Maximum and minimum daily temperatures (T2M_MAX / T2M_MIN), and corrected total precipitation (PRECTOTCORR). These variables were chosen for their relevance in modeling the environmental conditions that directly influence crop performance (Table 1).

Table 1. Variables and data sources

Variable Name	Label	Unit	Source
Temperature at 2m	T2M	°C	NASA POWER
Max/Min Temperature	T2M_MAX / MIN	°C	NASA POWER
Relative Humidity	RH2M	%	NASA POWER
Total Precipitation	PRECTOTCORR_SUM	mm	NASA POWER
Wind Speed	WS2M	m/s	NASA POWER
Agricultural GDP	AGRI_GDP	USD	World Bank

Source: realized by ourselves

These variables were chosen for their relevance in modeling the environmental conditions that directly influence crop performance (Table 1). Specifically, they were selected due to their direct physiological influence on crop growth and water balance (see fig. 1).

4.3 Data Preparation

The economic dataset, sourced from the World Bank, spans from 1990 to 2020 and provides annual agricultural GDP figures for 26 Asian countries. Complementary climate data for the same period were obtained from NASA's POWER platform, offering a consistent basis for analysis. These annual datasets were directly used to train machine learning models without requiring temporal aggregation. However, in South Korea's case, a more granular approach was taken by using yearly climate data that was extracted and utilized as inputs to the trained model to estimate provincial-level yearly agricultural GDP. This methodology made it possible to capture the short-term climate changes and fluctuations allowing us to assess their localized effects on agricultural productivity across South Korea's distinct climatic regions. The inclusion of 1990–2020 data from 26 Asian countries provided a diverse training base of 806 observations, which allowed the ANN to learn global climate-agriculture patterns before being fine-tuned for the specific provincial dynamics of South Korea.

4.4 Data quality and verification

Before proceeding with the analysis, we made sure that both the climate and economic datasets were carefully validated, undergoing rigorous and careful validation procedures to ensure their accuracy and reliability. This involved the checking for missing values, outliers and making sure the data stayed consistent and reliable over the time period spanning from 1990 to 2020. Any issues or anomalies that were detected were systematically addressed using data cleaning techniques enhancing the integrity of the inputs. This careful and rigorous preprocessing ensured that the datasets were not only trustworthy but also ready for robust machine learning applications, specifically in this study's case Artificial Neural Network. However, it should be noted that reanalysis data may smooth localized climatic extremes.

4.5 Machine learning models

This main objective with the chosen model in this study is examining the relationship between climate variables and agricultural GDP. To address this objective, we used Artificial Neural Networks (ANNs). ANN was selected for its ability to model nonlinear relationships and interactions among climatic variables. ANNs are inspired by the structure and functioning of biological neurons in the human brain, they are capable of uncovering intricate patterns in the data by iteratively adjusting the strength of connection between neurons through repeated training cycles. This adaptive learning process allows the network to refine their predictive accuracy over time. Thanks to their flexibility and their robust ability to handle complex and varied data, ANNs

are particularly well-suited for capturing the multifaceted climatic dynamics that influence agricultural productivity. These characteristics makes ANNs an effective tool for modeling the real-world complexities of climate agriculture interactions and dynamics (see Equation 1).

The output of the neural network is computed using the following formulation (see fig. 2):

$$Y = f(W_2 \cdot f(W_1 \cdot X + b_1) + b_2) \tag{1}$$

X is the input vector (climatic variables),

W_1, W_2 are weight matrices,

b_1, b_2 are biases,

f is the activation function.

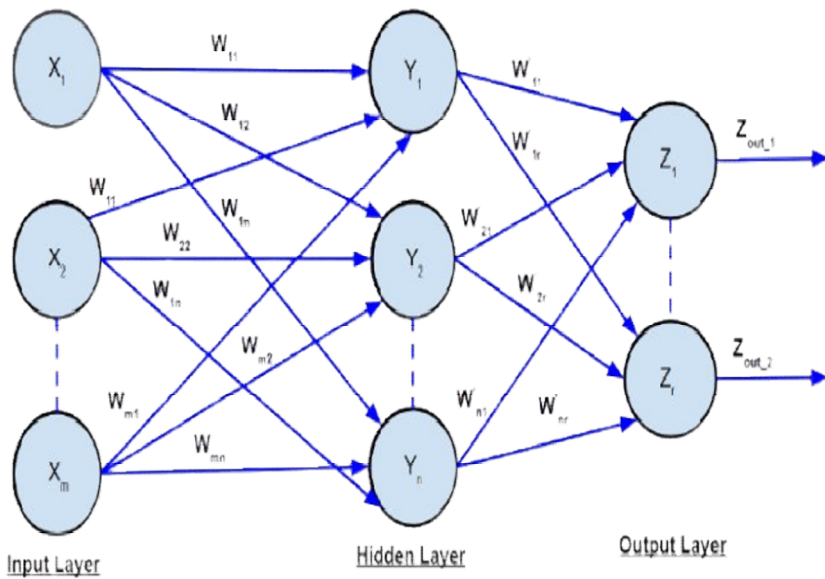


Fig. 2. Neural Network Structure

Source: www.geeksforgeeks.org

To ensure the reproducibility of the results, the Artificial Neural Network (ANN) was implemented using the neuralnet package in R Studio. The architecture consisted of a multi-layer perceptron (MLP) with a single hidden layer containing five neurons, a configuration chosen to balance predictive power with the prevention of overfitting given the dataset size.

The model utilized the Logistic Activation Function (Sigmoid) for the hidden layer to capture the nonlinear relationships between climatic variables and agricultural

GDP. Training was performed using the Resilient Backpropagation algorithm with weight backtracking. The convergence threshold was set to 0.01 for the partial derivatives of the error function, ensuring robust optimization across the 10-fold cross-validation process. All input variables were normalized to a [0,1] range prior to training to ensure uniform weight distribution across diverse units such as millimeters (precipitation) and degrees Celsius (temperature). The ANN model identifies predictive relationships rather than causal mechanisms. However, it is important to note that the ANN model identifies predictive relationships rather than causal mechanisms.

The chosen model was applied to yearly climatic data in South Korea to generate precision forecasts of crop related GDP at the provincial level. This approach allows for an accurate prediction of the agricultural GDP both on a provincial and yearly level. This is especially important in the case of South Korea, due to its varied topography and latitude which vary widely and lead to significantly different weather patterns between regions. For instance, southern provinces like Jeollanam-do and Gyeongsangnam-do typically experience milder winters and heavier monsoonal rainfall, northern regions on the other hand, such as Gangwon-do face harsher winters and shorter growing seasons. These annual projections provide valuable insights into seasonal agricultural production trends in each province, this is essential for making informed and strategic resource distributions and allows for a more efficient management of climate related risks, such as typhoons, droughts or unseasonal frosts which can severely affect crop yields. The model chosen in this study was trained for each province alone to account for the unique interactions between climatic conditions and agricultural productivity. This allowed us to generate tailored region-specific forecast that supports better planning and policy making in the agricultural sector.

4.6 Model evaluation

In the model evaluation, we wanted to make sure that the models were reliable and not just tailored to one particular datasets, that is why each model underwent 10-fold cross validation using climate and economic data from 26 Asian countries. This process involved partitioning the dataset into multiple subsets or "folds", to thoroughly test the model robustness and minimize the risks of overfitting. By ensuring that the model's precisions were not overly dependent on any single data fragment, this is a widely used technique that helps enhancing the credibility and trustworthiness of the forecasting results.

The model performance was measured by a cross validation on the training data using standard statistical metrics, such as Root Mean Square Error RMSE (see equation 3), Mean Absolute Error MAE (see equation 2), and the coefficient of determination R^2 (see equation 4). These classic evaluation metrics served to quantify the model's accuracy. RMSE (see equation 3) gives a sense of how big prediction errors are on average capturing the magnitude of forecast errors, R^2 (see equation 4) tells us how much of the variation in agricultural GDP the model is able to explain and MAE (see

equation 2) measures the average absolute difference between predicted and actual values, regardless of if they are positive or negative. Together, these metrics gave us a clear picture of how accurate and reliable the forecasts were.

$$MAE = \frac{1}{n} \sum_{i=1}^n (Y_i - \hat{Y}_i)^2 \quad (2)$$

$$RMSE = \sqrt{MAE} \quad (3)$$

$$R^2 = \frac{\sum_{i=1}^n (Y_i - \bar{Y})(\hat{Y}_i - \bar{\hat{Y}})}{\sum_{i=1}^n (Y_i - \bar{Y})^2} \quad (4)$$

5 Results

Coefficient of Determination (R2): 0.84.

Root Mean Square Error (RMSE): 0.55.

Mean Absolute Error (MAE): 0.74.

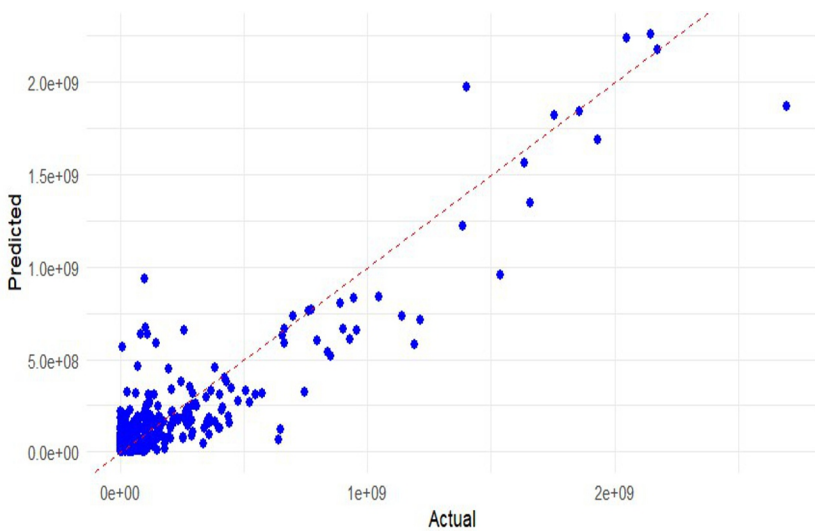


Fig. 3. Comparison of Predicted vs. Actual Agricultural GDP (Billion USD)

Source: realized by ourselves via visualization in R

Fig. 3 visualizes the performance of the ANN model in estimating agricultural GDP from climatic variables in South Korea. It is comparing the predicted agricultural GDP on the y axis with the actual observed agricultural GDP on the x axis, with the blue dots representing the individual prediction observation pairs and the red dashed line representing the perfect prediction where predicted GDP equals Actual GDP. The majority of the points lie close to the red line indicating a strong linear agreement between the predicted and actual agricultural GDP. This visual consistency supports quantitative performance metrics such as the R^2 of 0.84 (see equation 4) indicating a high explained variance, a RMSE of 0.55 (see equation 3) and a MAE of 0.74 (see equation 2) reflecting a relatively small average error. This suggests strong predictive performance of the ANN model in capturing the underlying relationship between climate variables and agriculture GDP in South Korea.

In exploring the error distribution and model bias we notice that we have an accurate low-to-mid-range predictions, precisely in the lower values in the actual GDP 0 to $\sim 5e+08$, we notice a clustering of blue points around the red line. This indicates that the model performs particularly well in the prediction of the GDP for provinces with smaller agricultural output, this is crucial as many of South Korea's provinces have small contributions to the agricultural GDP. With values increasing beyond $\sim 1e+09$, we notice that some blue points tend to fall below the red line, this indicates a slight underestimation bias in high output scenarios, this model tends to predict values lower than actual for top producing South Korean provinces. These variance patterns may reflect structural differences in regional production scales. Finally, few blue points (e.g., one with actual GDP $> 2.5e+09$ and predicted $\approx 1.9e+09$) deviate significantly from the reference line. These could be due to high yield years or measurement anomalies. This variance in the prediction errors increasing slightly with actual GDP is a phenomenon known as heteroskedasticity, reflecting a common modeling challenge relying on the fact that large scale economies often have higher natural variance and uncertainty. There is no clear curvature or systematic deviation in the residuals, suggesting the model, fortunately, does not suffer from strong nonlinearity related misfit or misspecification.

From a policy or agricultural planning standpoint, the used ANN model is highly reliable for average and low GDP provinces and is reasonably accurate for high value regions, with errors mostly being underestimations, which is preferable in risk sensitive decision contexts. The near linear trend also means a forecasting and scenario simulation based on climatic shifts is more than feasible with the used model.

This model achieved an R^2 value of 0.84, meaning that the model explains 84% of the variability in the actual agricultural GDP. This high degree of explanatory power suggests strong predictive performance and the suitability of ANN in capturing the complex, nonlinear relationships between climate and agricultural output. Moreover, the RMSE (0.55) (see equation 3) and MAE (0.74) (see equation 2) values are relatively low, reflecting accurate predictions with minimal deviation from real observations. These results validate the robustness of the model in generalizing across diverse regional climates while maintaining precision in localized forecasts. South Korea's climatic landscape is defined by its latitudinal span, mountainous terrain, and coastal influences. These factors contribute to substantial variations in climatic conditions across different provinces. Analysis of climate data distributions confirms these disparities. Jeju-do and Jeollanam-do, located in the southern and southwestern parts of the country, exhibit the highest levels of precipitation due to strong monsoonal activity and maritime effects. In contrast, Gangwon-do, with its mountainous geography in the northeast, has colder average temperatures and lower precipitation levels. Humidity shows relatively higher levels in Chungcheongnam-do and Jeollabuk-do, suggesting denser atmospheric moisture in these agriculturally active zones. Wind speed variability is most pronounced in Chungcheongbuk-do, possibly due to its topographic exposure and inland location. This climatic diversity underscores the necessity for a regionally tailored approach to modeling and policy-making.

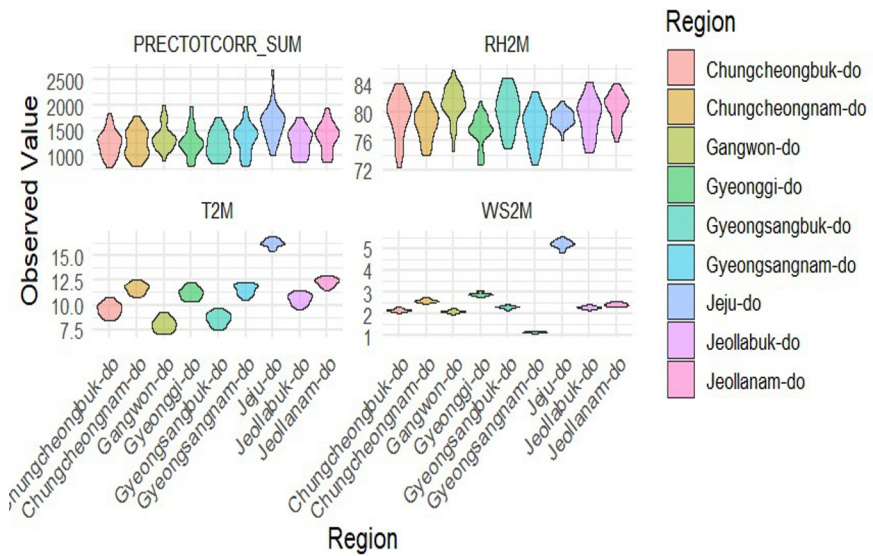


Fig. 4. Climate Variable Distributions Across Regions

Source: realized by ourselves via visualization in R

Figure 4 is a violin plot were used representing a comparative visualization of the distribution and variability of out four climate variables (Temperature at 2 m, Relative Humidity at 2 m, Total Precipitation and Wind speed at 2 meters), across nine provinces. Each subplot is a violin plot which combines both a boxplot showing median and interquartile range as well as a kernel density estimate showing distribution shape and spread, this allows for insight into central tendencies, dispersion, skewness and inter regional differences.

Among the four climatic variables assessed, we noticed that precipitation (PRECTOTCORR_SUM) emerged as the most influential factor affecting agricultural GDP across nearly all the nine regions. Whoseits correlation with the actual GDP was the strongest in the following provinces: Chungcheongnam-do (0.87), Jeollanam-do (0.85), Jeollabuk-do (0.82), and Gyeonggi-do (0.80). For instance, Jeollanam-do exhibit the highest median precipitation, suggesting stronger monsoon effects or proximity to the ocean, Chungcheongnam-do also have broader distributions, indicating higher intra annual variability, which may challenge agricultural planning and Gyeonggi-do displays a moderately high precipitation range with relatively stable distribution, as it is one of Korea's key agricultural province, consistent rainfall in this region provides a reliable base for high yield crops like rice and vegetables. These four provinces rely heavily on rainfall for paddy cultivation and other water intensive crops, which makes them particularly vulnerable to the precipitation anomalies.

When it comes to the provinces affected the most by precipitation, it is crucial to also explore how they adapt to its effects. For instance, Jeollanam-do is affected the most by monsoon and its proximity to the ocean and its adaptation to these effects rely on employing expansive irrigation networks and flood resistant rice strains to manage both excess and insufficient rainfall. As of Chungcheongnam-do, it knows a higher intra annual variability which affects agricultural planning, to mitigate this, the province has invested in climate resilient farming practices, for example rainwater harvesting systems and predictive agro-meteorological services to influence planting schedules. On the other hand, Gyeonggi-do displays a moderately high precipitation range with a relatively stable distribution compared to the other two provinces explored. Farmers in this region use precision irrigation systems and climate monitoring to optimize water usage and protect crops from unexpected droughts and flooding. And in Jeollabuk-do, local authorities support farmers by subsidies for greenhouse structures and modernized drainage systems to ensure stability in periods of rainfall uncertainty, as the region is known for its agricultural intensity.

When it comes to relative humidity (RH2M), it exhibits moderate importance in some provinces as exploring the data shows that Chungcheongnam-do and Jeollanam-do display the highest medians, suggesting consistently humid conditions favorable for crops needing moist environments, while Gangwon-do and Gyeongsangnam-do exhibits lower medians and narrower spreads, pointing to drier conditions, potentially affecting water sensitive crops or increasing evapotranspiration stress. This means that there is a significant correlation, implying that atmospheric moisture may affect crop respiration and water retention in soil. Compared to precipitation, relative humidity effect is less pronounced but important for plant transpiration rates, disease risk

and irrigation strategies. Higher humidity supports continuous plant growth but could increase fungal threats.

In response to the humidity effects, provinces such as Chungcheongnam-do and Jeollanam-do adapted by promoting crops that thrive in moist and humid environments, they also implemented smart investments in early detection and management strategies for humid related plant diseases for example fungal infections. Also, in these two provinces, extension services recommend crop rotation systems to reduce prolonged exposure of fields to high moisture crops. However, drier provinces like Gangwon-do and Gyeongsangnam-do they implemented climate resilient farming practices. In Gangwon-do, known for its mountainous landscape and short growing seasons, farmers have adopted drip irrigation systems and mulching techniques to conserve soil moisture hence counteracting to the effects of humidity. Furthermore, in the region farmers adapted their crop calendars to align planting and harvesting with narrow windows of optimal humidity. In Gyeongsangnam-do on the other hand, as the region is known by its diverse input including both inland and coastal farming zones, adaptation included the use of controlled environment agriculture, such as greenhouse cultivation counteracting the dry atmospheric conditions in the region. The farmers in this province also started using drought and stress resilient crop varieties, particularly in areas vulnerable to higher evapotranspiration, ensuring stable yields even under humidity stress.

Temperature, while generally less impactful, plays a critical role in Gangwon-do as it has the lowest median temperature, with a broader spread, reflecting cold winters and milder summers due to high elevation where a colder climate and shorter growing season make thermal conditions pivotal for agricultural success. While Jeju-do stands out with the highest temperature median and tightest distribution, reflecting its subtropical climate. With central provinces such as Chungcheongbuk-do, Gyeonggi-do show moderate, relatively consistent temperature ranges. This means that temperature is a strong determinant of crop types, as Gangwon-do may need cold-tolerant varieties, while Jeju-do is suited for subtropical crops like citrus. The narrower ranges in climatic variations seen in southern provinces imply climatic stability, which is beneficial for maintaining consistent and predictable harvest cycles.

When adapting to temperature effects, even with its smaller impact compared to precipitation, each region adapted using its own strategy. Jeju-do stands out with both the highest temperature median and the most consistent temperature range in South Korea. This stable and warm climate profile is ideal for growing specialty crops, for example citrus fruits, tea and subtropical vegetables. In response to the temperature effects, the Jeju island focused on cultivating high value niche crops that thrive in warmer weather. In this province, farmers also utilized advanced orchard management practices and protective netting systems to manage temperature extremes and typhoon risks. On the other hand, central provinces like Chungcheongbuk-do and Gyeonggi-do are known for their relatively consistent temperature ranges this stability in temperatures favors diverse crop farming and allows double cropping in some areas. In these two areas, adaptations include flexible planting calendars and rotational cropping to optimize land use. The stability in temperatures, ensures farmers in those regions can rely on relatively predictable harvest cycles, this is crucial for main-

taining income stability. Gangwon-do must invest in infrastructure and cold resistant practices, while Jeju-do uses its warm weather to specialize in unique crops. Meanwhile, central provinces benefit from climatic and temperature stability that enhances efficient and consistent agricultural planning.

Wind speed, overall, had the least influence on GDP across the nine provinces, though its moderate importance in Chungcheongbuk-do suggests localized effects, possibly due to wind-induced soil erosion or impacts on pollination. Exploring the data shows that Jeju-do exhibits the highest wind speeds and widest range, this aligns with its coastal and island geography, where exposure to oceanic air masses increases wind intensity. In Chungcheongbuk-do and Gangwon-do we notice moderate wind speeds with moderate variability. While Jeollabuk-do and Jeollanam-do have the lowest and most stable wind speeds, which may benefit crops that are sensitive to physical stress. While wind is not the primary factor for yield as we explored here, it does have an impact on pollination, erosion and crop stability. Higher speeds in Jeju may pose risks during typhoon season and low wind areas may face less mechanical damage but also less natural cooling.

When it comes to the adaptation of the effects of wind speed across the provinces explored, Chungcheongbuk-do and Gangwon-do, experience moderate wind speeds, farmers in those provinces have implemented the planting of windbreaks, for example the planting of rows of tall trees or artificial barriers to reduce soil erosion and physical damage to crops due to wind. They also use mulching and cover crops preventing topsoil loss in windy periods. On the other hand, Jeollabuk-do and Jeollanam-do are characterized by the lowest and most stable wind speeds across South Korea's provinces, this is advantageous for crops that are sensitive to physical disturbances. However, reduced air movement can also be a limiting factor, as air movement is a natural cooler and pollination inducer. To counter this, farmers in those areas adopted a mixed cropping pattern and an inter row spacing techniques to facilitate air circulation.

The inter-regional observation and its agricultural implications of the figure above, provinces with climatic extremes such as Jeju-do which is the warmest, windiest and one of the wettest regions supports subtropical agriculture like citrus and tea, Gangwon-do is the coldest and among the driest regions, suited for hardy and short season crops like potatoes and barley, while Jeollanam-do and Jeollabuk-do receive ample precipitation, moderate temperature and stable wind ideal conditions for high yield staple crops like rice. Regions with narrower distributions provide more stable agro-climatic conditions, simplifying crop management. And broader distributions, indicate climate volatility, which demands flexible farming strategies and possibly climate insurance schemes. The use of the violin plots offers clear visibility into data density and spread, which bar or box plots cannot, and combining all four variables allows us to reach a multi-dimensional climate risk profiling across all provinces. This visual analysis used in this study, underscores the regional climatic diversity of South Korea, playing an important role in agricultural outcomes. Going from humid and wind exposed Jeju-do to cool and mountainous Gangwon-do, this diverse microclimate necessitate region-specific agricultural policies and crop planning strategies. This climate heterogeneity validates this study's use of provincial-level machine learning models

to estimate agricultural GDP and tailor climate resilience efforts accordingly (see fig. 5).

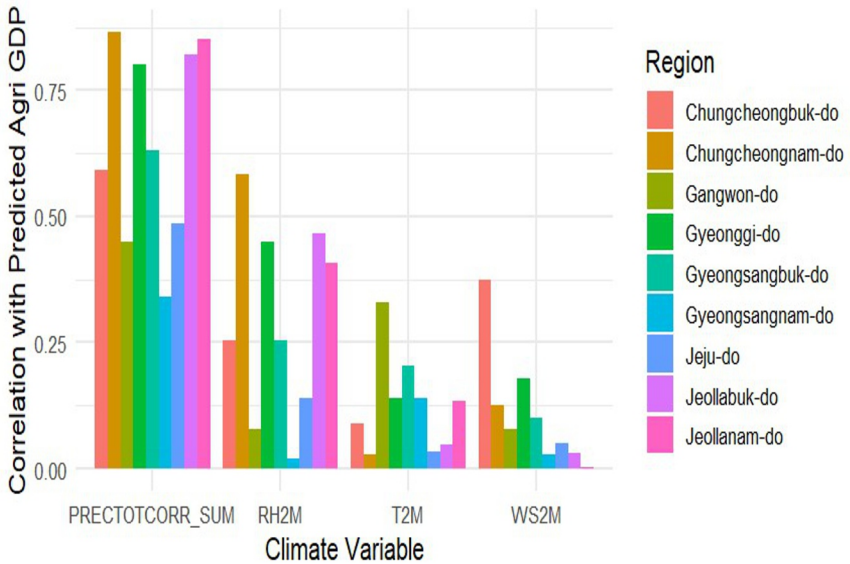


Fig. 5. Variable Importance Mapping by Province

Source: Realized by ourselves via visualization in R

In light of the regional variability in climate sensitivity, several provinces stand out for targeted policy intervention. Chungcheongnam-do, with its high sensitivity to both precipitation and humidity, requires enhanced water management infrastructure and early warning systems to mitigate the risks of flooding and drought. Jeollanam-do and Jeollabuk-do, which exhibit strong climatic correlations, would benefit from investment in irrigation and rainwater harvesting systems to ensure year-round water availability. Gangwon-do, which is uniquely responsive to temperature variations, should prioritize cold-resistant crop varieties and frost-prevention strategies. In contrast, Jeju-do displayed weak correlations across all variables, which may be attributed to factors beyond climate, such as technological inputs, crop diversification, or protected cultivation. These findings emphasize the necessity of region-specific strategies rather than a one-size-fits-all policy approach.

In this bar chart we tried to visualize the correlation coefficient between predicted agricultural GDP and each of the four climate variables used in this research, disag-

gregated by province coordinated by color. The height of each colored bar indicates the importance, measured by correlation strength of each particular variable predicting agricultural GDP in each region. Providing us a comparative perspective on which climate variable contributes most significantly to agricultural GDP forecasting at a provincial level in South Korea.

This analysis shows that, across all provinces, precipitation is clearly the dominant and influential climate variable, with the highest correlations found in the four provinces: Chungcheongnam-do with 0.87, Jeollanam-do with 0.85, Jeollabuk-do with 0.82 and Gyeonggi-do with 0.80. With such values we confirm that agricultural productivity in these provinces is highly sensitive to rainfall, this is consistent with those provinces cropping systems, particularly rice cultivation which is water intensive. Furthermore, even in provinces with lower precipitation relative importance, the variable still holds the highest or second highest correlation, for example in both the provinces of Gyeongsangnam-do and Gangwon-do, emphasizing that precipitation has a universal role in crop success across the diverse agroclimatic regions.

Relative humidity exhibits a mid-level importance following precipitation, but its influence is more regionally variable. This influence is stronger in three provinces, which are Chungcheongnam-do with 0.58, Jeollabuk-do with 0.47 and Gyeonggi-do with 0.45. This suggest that relative humidity has a critical supporting role in those provinces, mostly affecting evapotranspiration rates, plant water retention, and vulnerability to moisture-sensitive pests and diseases. On the other hand, other regions like Gangwon-do and Gyeongsangnam-do have a low correlation with relative humidity, lower than 0.1, implying that relative humidity is not a major limiting factor in those provinces, most likely due to naturally drier climates and adaptive agricultural practices.

For temperature, it is showing a weaker correlation compared to precipitation and humidity. However, temperature does become important in certain contexts. For example, in Gangwon-do which has a correlation to temperature of 0.33, being the highest temperature sensitivity across all provinces. This is likely due to its colder climate and short growing season. Other provinces like Chungcheongnam-do and Jeollabuk-do exhibit a very low correlation to temperature below 0.05, due to temperature stability and the use of protective cropping systems like greenhouses. While Gyeongsangbuk-do and Gyeonggi-do display moderate values suggesting some influence on seasonal crop planning.

For the fourth variable, wind speed consistently shows the lowest correlation values compared to all the other variables, often below 0.1 across all provinces. However, we notice some exceptions such as Chungcheongbuk-do which has a correlation of 0.38, notably higher than other regions, hinting at a possible impact from wind driven erosion and pollination effects for specific crop systems. Other provinces, for example Jeollabuk-do, Jeollanam-do and Jeju-do show negligible correlation values with wind speed, confirming that this variable does not directly drive large scale agricultural output, though it may have some influence on micro-scale crop management.

In the context of a cross regional observation, we find that the provinces of Chungcheongnam-do and Jeollanam-do consistently respond to both precipitation and humidity, meaning that they may benefit from enhanced water management infrastruc-

ture and disease forecasting systems, as compared to other regions they are the most sensitive across all variables. Gangwon-do requires an implementation of strategies focused on frost resilience and thermal adaptation, given the elevated importance of temperature in this province. Provinces of Jeollabuk-do and Gyeonggi-do show a moderate to strong correlation across multiple variables, meaning that they have direct climate impacts in productive and diverse cropping. This highlights the importance and value of region-specific climate-agriculture modeling, machine learning models like the one used in this study (ANN) are essential for capturing this nuanced variability. In such contexts, one size fits all agricultural policy would likely miss critical region-specific dynamics, meaning that adaptive climate smart policies should be prioritized. For example, provinces that are more sensitive to rainfall should invest in irrigation and water capture systems, while greenhouses and temperature control are more adapted in cold climate provinces and integrated pest and disease management is the key for provinces most affected by humidity. The variable importance by province graph we used in this study, is a powerful diagnostic tool allowing us to understand which climate variables matter the most where. While precipitation is the universally dominant variable, the differential roles of relative humidity, temperature and wind speeds underscore the need for tailored regional strategies. This supports the study's broader objective of leveraging machine learning for fine-grained, actionable climate adaptation in agriculture across all of South Korea.

Table 2. Regional Correlation Matrix of Climatic Variables and Predicted Agricultural GDP

Region	PREC TOTCO RR_SU M (mm)	RH 2M (%)	T2 M (C°)	WS2 M (m/s)	Agri_ GDP (USD)
Chung- cheong- buk-do	0.5923 213	0.25 53158 3	0.09 06919 3	0.3754 76473	3.410 837197
Chung- cheong- nam-do	0.8663 389	0.58 42856 4	0.02 79135 7	0.1270 10965	5.934 53069
Gang- won-do	0.4481 984	0.07 77217 1	0.32 99977 0	0.0781 82352	1.778 022772 999999 8
Gyeong- gi-do	0.8003 093	0.44 98307	0.13 84188	0.1781 75251	4.863 327504

		8	7		000001
Gyeong-sangbuk-do	0.6309 353	0.25 54489 9	0.20 45515 2	0.1011 55394	3.460 745611
Gyeong-sangnam-do	0.3413 873	0.02 02408 2	0.14 05115 8	0.0270 21219	1.868 033151
Jeju-do	0.4862 781	0.13 87463 1	0.03 24390 1	0.0491 64032	3.172 416657 999999 5
Jeolla-buk-do	0.8192 447	0.46 54954 2	0.04 73215 5	0.0305 91934	5.454 122341
Jeolla-nam-do	0.8515 028	0.40 85396 2	0.13 52228 3	0.0042 29855	5.175 60189

Source: Realized by ourselves via visualization in R

When analyzing the agricultural GDP (Agri_GDP) values in conjunction with the climate variable correlations shown in table 2, we notice a clear pattern emerging that highlights the interpretation of climatic influence over agricultural productivity and production. Provinces such as Chungcheongnam-do, Jeollanam-do, Jeollabuk-do, and Gyeonggi-do, report the highest projected agricultural GDPs of respectively 5.93 B USD, 5.18 B USD, 5.45 B USD and 4.86 B USD. These provinces also show the strongest correlations with precipitation and to a lesser extent with relative humidity, confirming that agriculture in these provinces is not only climate sensitive but also highly productive. While other provinces such as Gangwon-do and Gyeongsangnam-do with respectively agricultural GDPs of 1.78 B USD and 1.87 B USD, this being the lowest agricultural GDP figures which aligns with their relatively weak correlations with precipitation and humidity, and in the province of Gangwon-do a higher sensitivity with temperature variable instead. This contrast between the different South Korean provinces reinforces the fact that precipitation is not just a statistically dominant predictor, but also a strong economic driver of agricultural productivity in the different regions. Furthermore, the island of Jeju-do presents an interesting case

with mid-level GDP of 3.17 B USD even with its weak correlations across all climatic variables. This means that other non-climatic factors play a decisive role in sustaining the agricultural productivity in Jeju-do, such as infrastructure, technology and policy interventions.

In this section we focused on evaluating the historical and present-day relationships between climatic variable and agricultural GDP, we used correlation analysis and ANN model prediction accuracy. However, it is equally important to extend these analyses towards the future. As the climatic context is rapidly changing constantly, forecasting becomes an indispensable tool for anticipating regional agricultural outcomes and shaping policy interventions ahead of time, enabling proactive adaptation strategies. This is crucial when it comes to agricultural productivity where planning cycles are seasonal and capital investments require long term foresight. The Artificial Neural Network model used and validated in this study provides a reliable framework for this kind of forecasting, as it is capable of capturing nonlinear and regionally heterogeneous interactions between climatic variables and agricultural GDP. When applying this model to future climate projections of 2030, we aim to generate spatially explicit forecasts of agricultural GDP at a provincial level. These forecasts not only highlight potential vulnerabilities but also serve as a decision support tool for policy-makers seeking to climate proof South Korea's agricultural sector.

5.1 Forecasted Agricultural GDP by province (2030)

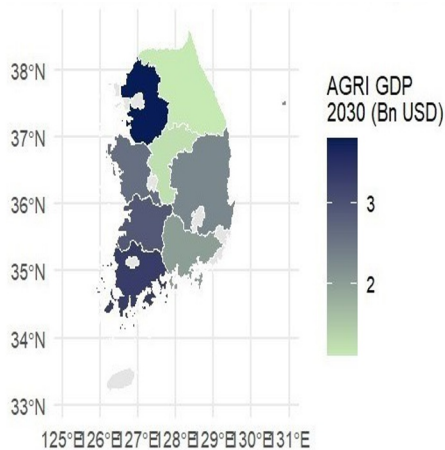


Fig. 6.Forecasted Agricultural GDP by Province (2030)

Source: ANN Forecast based on Climate Inputs

Fig. 6 presents the forecasted agricultural GDP across all South Korean provinces in the year 2030. The color scale used represents different level of agricultural GDP in billion USD, with the light green shades indicating lower agricultural GDP and the darker blue shades indicating higher agricultural GDP. The forecast is based on the Artificial Neural Network used in this study. This map allows us to understand that in the northernmost province of Gangwon-do we have a lower agricultural productivity or smaller sector value, lower than 2 billion USD. In the central and southeastern provinces, for example Chungcheong-do and Gyeongsang-do, they display moderate tones reflecting mid-range forecasts between 2 to 2.5 billion USD. And on the southwestern and coastal regions such as Jeollanam-do and Jeollabuk-do, they are shaded in dark blue, signaling the highest agricultural GDPs above 3 billion USD. Meaning that the southern regions tend to exhibit a higher agricultural GDP forecasts which aligns with the fact that these areas have more arable land and rice paddies and experience warmer temperatures and higher precipitation. While northern regions which are colder, mountainous and less agriculturally intensive show lower agricultural GDP values.

This map reveals how climate change reshapes regional agricultural productivity, as the decline in the agricultural GDP results from the increased weather variability, reduced growing season length and low crop resilience to climate extremes. The map also highlights the provinces in need of investments in the agricultural innovation, irrigation and crop diversification, while provinces with high agricultural GDP need climate risk mitigation strategies to sustain their outputs. The forecasted agricultural GDP by province in 2030 made by using the ANN forecast is a useful tool for decision makers as it can aid in targeted climate adaptation and agri-policy planning.

6 Discussion

The objective of this research is to assess the impacts of climate change on agricultural GDP in South Korea using Artificial Neural Networks. This discussion builds upon the analytical results presented above, emphasizing the implications, limitation and future potential research directions.

The following dashboard synthesizes the key climatic sensitivities and projected economic impacts across representative provinces (see table 3):

Table 3.Summary of Regional Climatic Sensitivities and Strategic Policy Directions

Province	Dominant Variable	Correlation (R)	Primary Policy Recommendation
Chungcheong-	Precipitation	0.87	Enhance water management & warning sys-

nam-do			tems.
Jeollanam-do	Precipitation	0.85	Invest in irrigation & rainwater harvesting.
Gangwon-do	Temperature	0.33	Prioritize frost-resistant crop varieties.
Jeju-do	Tech/Infrastructure	Weak	Promote digital agriculture & vertical farming.

Source: Realized by the authors based on ANN model results and correlation analysis

6.1 Interpreting Climatic Sensitivities

The results confirm that climatic variable, particularly precipitation, influence significantly agricultural productivity across South Korea. The high correlation between precipitation and agricultural GDP in water-intensive provinces like Jeollanam-do, Jeollabuk-do, Chungcheongnam-do, and Gyeonggi-do emphasizes the dominant role of rainfall in shaping regional agricultural output. Relative humidity emerged as the second most influential factor, with mid-level but regionally distinct effects, particularly in moist zones like Chungcheongnam-do and Jeollabuk-do.

Temperature and wind speed had relatively lower but still contextually important effects. Temperature was especially relevant in colder, mountainous areas such as Gangwon-do, suggesting that regions with short growing seasons are particularly vulnerable to thermal shifts. Wind speed, although less impactful overall, had moderate effects in certain regions (e.g., Chungcheongbuk-do), possibly due to topographical exposure or sensitivity to physical crop stress.

6.2 Regional Disparities and Agricultural Vulnerability

The regional climatic heterogeneity evident in South Korea's geography—ranging from the warm, humid coastal zones of Jeollanam-do to the cold, mountainous inland of Gangwon-do—necessitates differentiated agricultural strategies. The forecasting to 2030 suggests that southern provinces are likely to remain the most agriculturally productive, while northern areas may continue to lag due to topographic and climatic limitations. Forecasts should be interpreted as scenario-based projections rather than precise predictions.

These disparities reinforce the need for climate adaptation policies tailored to local conditions. Regions like Jeollanam-do and Jeollabuk-do could enhance resilience by continuing investments in irrigation and flood control, while Gangwon-do may

strengthen its agricultural sector by focusing on frost-resistant crops and thermal protection infrastructure.

6.3 Climate Sensitivity and Regional Policy Implications

Given the regional variability in climate sensitivity, many South Korean provinces stand out as clear priorities for targeted policy intervention. For instance, Chungcheongnam-do, which knows a high sensitivity to both precipitation and relative humidity, would highly benefit from improved water management infrastructure and early warning systems to mitigate risks such as flooding and drought. Jeollanam-do and Jeollabuk-do on the other hand, show strong climatic correlations especially with precipitation, in these provinces investments in irrigation and rainwater harvesting systems could support a stable year-round water availability. In contrast, Gangwon-do, which is uniquely sensitive to temperature variations, may prioritize cold-resistant crop varieties, frost prevention measures and thermal buffering techniques. While Jeju-do exhibited weak correlations across all the four climatic variables explored in this study, this may mean that this province is more affected by other factors beyond climate, for examples technological inputs, crop diversification and protected cultivation, rather than climatic factors. These findings highlight the crucial role of region-specific strategies rather than a one-size-fits-all policy approach.

6.4 Toward Regionally Differentiated Climate-Smart Agriculture

In the light of provincial variability of agriculture to climatic sensitivity explore in this study, it is undeniable that targeted, data driven policies are crucial for addressing the specific climatic challenges the different South Korean provinces face. Those tailored policies should be explored with each climatic variable in mind.

Precipitation-Sensitive regions.

Regions such as Chungcheongnam-do, Jeollanam-do, Jeollabuk-do and Gyeonggi-do, have the highest correlations between agricultural GDP and precipitation highlighting their vulnerability to both excess rainfall and seasonal droughts. These regions could enhance their resilience by investing in large scale irrigation infrastructure, including smart drop and sprinkler systems. Expanding rainwater harvesting networks at the farm and community level may strengthen water security. They could support climate-resilient rice varieties that can withstand both flood and drought stress. Introducing seasonal agro-meteorological forecasting services could also be beneficial to inform planting and harvesting schedules, while subsidies for water efficient technologies, such as soil moisture sensors and automated irrigation timers, may further strengthen resource management.

Temperature-Sensitive regions.

Provinces, such as Gangwon-do and to a lesser extent Gyeongsangbuk-do, where temperature plays a decisive role due to short growing season, frost risks and cold winters, could strengthen agricultural stability by developing and promoting cold resistant crop varieties, for example barley, potatoes and leafy greens. They may enhance production by expanding greenhouse farming with thermal insulation and solar powered heating and introducing frost early warning systems to help farmers take preemptive actions. These regions could also support agroforestry and windbreak plantations to buffer temperature extremes and provide training programs for altitude specific crop calendars.

Humidity-Sensitive regions.

Regions like Chungcheongnam-do, Jeollabuk-do and Gyeonggi-do, which are particularly affected by moisture related issues such as fungal diseases, mold and reduced evapotranspiration efficiency, could benefit from promoting integrated pest disease management (IPDM) programs tailored to high humidity zones and supporting ventilated greenhouse designs and humidity control systems for example dehumidifiers and mist control. They may strengthen disease management by introducing early detection technology for fungal and bacterial outbreaks for example smart sensors and drone-based scouting. Furthermore, offering incentives for crop diversification could reduce prolonged humidity exposure in mono cropped systems, and creating decision support platforms may help alert farmers to risky humidity thresholds.

Wind-Sensitive regions.

Those provinces could enhance crop protection by establishing windbreak systems, such as tree belts and artificial barriers in open farm lands. They may encourage the use of low profile and wind tolerant crop varieties, particularly during typhoon seasons. Also, introducing no till or reduced till farming practices could reduce topsoil loss, and supporting pollinator friendly planting arrangements may strengthen cross pollination even with wind disruptions.

Climate specific region.

For the specific provinces of Jeju-do, which exhibits a moderate contribution to the agricultural GDP even with its low correlations to all the four climate variables explore, could strengthen its agricultural sector through expanded research into protected cultivation systems, such as vertical farms and automated greenhouses while promoting climate neutral technologies for example hydroponics and aquaponics. The region may also support digital agriculture, such as AI based crop monitoring and

autonomous farm machines. Enhancing agricultural insurance schemes could serve as an interesting approach to buffer non climatic risks such as market volatility and input costs. All while potentially positioning Jeju-do as a pilot zone for high tech agriculture policy innovations, that could trickle to all the other South Korean provinces.

The explored policy recommendation underscores the importance of precision policy design in South Korea. The recommendation aligns with this study's objective of using machine learning not just a forecasting tool but as a decision support mechanism in the climate adaptation. South Korea could position itself as a global model for climate resilient agriculture in the face of climatic uncertainties through region specific strategies and tailored scalable national frameworks.

7 Limitations

While this study provides key insights into the impacts of climate change on South Korea's agriculture, using machine learning, many limitations need to be understood to properly frame the interpretation of the results and their applicability in the South Korean context.

A crucial limitation lies in the undeniable fact that South Korea's economy does not rely on agriculture. As of 2023, agriculture contributed less than 2% of the national GDP of the country, as the pillars of South Korea's economy are its industry and service sector. The low economic reliance on agriculture dilutes national urgency in addressing the agricultural vulnerabilities discussed in this study. However, it is undeniable that agriculture is important and plays a critical role in every economy, especially the South Korean economy as it can provide food security, rural livelihoods, cultural heritage and ecological sustainability. This means that even with its lesser weight to the economy, agriculture has a social and strategic importance in South Korea, justifying the need for the implementation of targeted tailored climate adaptation strategies in its provinces.

Another fundamental limitation is that this study derived its national and provincial agricultural GDP indicators data from reanalysis datasets such as the NASA's POWER platform. This dataset is indeed robust but comes with limitations in spatial resolution and temporal granularity. Agricultural GDP data are available only at an annual interval, this is limiting and stops the model from detecting intra-annual variations and extreme events. Furthermore, climatic data are downscaled to the provincial level, which can obscure microclimatic differences within provinces. Especially in a country like South Korea which has a diverse topography. These constraints may result in averaging effects, masking localized sensitives or extreme anomalies.

Furthermore, even with the model being validated across data spanning 26 Asian countries, the ANN's performance and relevance may vary when used on other countries other than South Korea. Limiting the transferability of findings.

8 Conclusion

This study demonstrated that climate change has a significant influence on agricultural productivity on a provincial level in South Korea. Using Artificial Neural Networks (ANN), a non-linear relationship between climatic variables and agricultural GDP was uncovered, offering both retrospective insights and forecasted outputs for the year of 2030. The findings of this research show that precipitation is the most crucially dominant climatic variable, especially in water intensive agricultural regions in South Korea, for example Jeollanam-do and Chungcheongnam-do. Relative humidity came second when it comes to its correlation with the different regions of South Korea, playing a big role on a more local level. While temperature and wind speed showed the lowest correlations with modest and geographically specific impacts.

These differences in the sensitivity of the South Korean agriculture across the different climatic variables explored, underscores the importance of provincial specific climate adaptation strategies. As precipitation dependent provinces need to enhance irrigation infrastructure and water governance, temperature sensitive provinces require frost resilient crop varieties and thermal buffering. While regions influenced by relative humidity demand pest management systems tailored to their microclimatic dynamics. Furthermore, this study highlights that climate resilient and economically productive regions such as Jeju-do would benefit from protected cultivation, emphasizing the need to integrate non climatic variables into future models.

Beyond this research findings, it also underscores key limitations that needs to be addressed in future research. The current reliance on climatic predictors alone, limited data granularity and the assumption of static adaptation behaviors. While not diminishing the value of current finding, these limitations point towards a promising future in climate and agricultural research. Future research should integrate socio-economic variables and crop-specific data to enhance predictive accuracy.

This paper not only validates the need of machine learning in forecasting agricultural outcomes in the climate change context, but also offers a robust and important diagnostic tool for climate-smart policymaking. This research bridges a critical knowledge gap in the South Korean context, where national machine learning modeling of agricultural GDP remains scarce. This research contributes to South Korea's broader goal of building resilient, adaptative and sustainable agriculture future in the face of increased climate stress by combining analytical rigor with practical foresight.

9 CRedit Author Contribution Statement

- RAOUH ElMehdi: Conceptualization, Visualization, Methodology, Writing – original draft.

- CHERKAOUI Mounia: Supervision, Writing – review & editing.
- EN-NIA Samir: Data curation, Software (R Studio), Visualization, Writing – review & editing.
- LIOUAEDDINE Mariem: Supervision, Writing – review & editing.
- MANSOURI Zakaria: Resources, Methodology, Writing – review & editing.

Data availability

The data that support the findings of this study are available from publicly accessible databases:

- Climate data from NASA POWER Data Access Viewer: <https://power.larc.nasa.gov>
- Agricultural GDP data from World Bank Open Data: <https://data.worldbank.org>

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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